A STREAMER MODEL FOR HIGH VOLTAGE WATER SWITCHES

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Abstract

An electrical switch model for high voltage water switches has been developed which predicts streamer-switching effects that correlate well with water-switch data from Casino over the past four years and with switch data from recent Aurora/AMP experiments. Preclosure "rounding" and postclosure resistive damping of pulseforming line voltage waveforms are explained in terms of spatially-extensive, capacitive-coupling of the conducting streamers as they propagate across the gap and in terms of time-dependent streamer resistance and inductance. The arc resistance of the Casino water switch and of a gas switch under test on Casino was determined by computer fit to be 0.5±0.1 ohms and 0.3±0.06 ohms respectively, during the time of peak current in the power pulse. Energy lost in the water switch during the first pulse is 18% of that stored in the pulseforming line while similar energy lost in the gas switch is 11%. The model is described, computer transient analyses are compared with observed water and gas switch data and the results - switch resistance, inductance and energy loss during the primary power pulse - are presented.

Introduction

The generation of terawatt power pulses in high-current relativistic electron beam machines is limited primarily by the performance of switches at the input and output to the pulseforming line. Currently water-arc switches are most commonly used in these machines and are expected to dominate high-power switch technology for some time. One of the major deficiencies of water switch technology is the lack of a suitable model which accurately describes switch performance. The experimental difficulties of accurately measuring the resistance of the water arc and the energy dissipated in the switches in an actual accelerator are considerable. This research was directed towards achieving a better understanding of water-switch electrical behavior at Casino and Aurora/AMP with the ultimate goal of aiding the development of high-power generators with improved power output and energy-transfer efficiency.

The Casino generator (Figure 1) has a single output water switch from the pulseforming line into a transformer and diode load. A review of the pulseforming line voltage measurements taken routinely during the past four years reveals that the tip of the waveform near the negative-voltage peak is occasionally rounded. This rounding was previously thought to be due to switch closure occurring near the rounded peak in the pulseforming line's resonance-charging waveform. However, careful measurement of the Marx and pulseline electrical parameters revealed that the switch-rounding effect was entirely independent of the rounding associated with the resonant charging peak (Figure 2). Rounding is thus a normal characteristic of water-switch closure. Closure waveforms from gas switches[1] being tested on Casino confirmed that switch-rounding was much more pronounced with the water switch than with the gas switch. This prompted formulation of a more complete electrical model for the switch which postulated conducting bush/streamer formation as the origin of these observed electrical effects. In this paper the switch streamer model which was developed is described and then applied to switch-voltage waveforms from Casino and Aurora/AMP.

The Switch Model

Recent observations[2] of prebreakdown events in transformer oil with small (2 mm) point/plane gaps reveal that multiple electrical pathways or "bushes" grow subsonically from the cathode point. After these bushes enlarge a distance which is usually about one-half the gap spacing or less, a supersonic streamer bridges the gap. The streamer apparently emanates from the bush. Additional observations[2] in nitrobenzene by means of Kerr fringe patterns directly confirm that (1) the cathode bush is a conducting medium and (2) there is no space-charge distortion between the leading edge of the bush and the opposite plane electrode.

When the point electrode is made positive with respect to the plane only a supersonic tree bridges the gap. Positive streamer studies in dielectric fluids for gaps between 6 and 25 mm have furthermore revealed that the positive streamers are propagated at constant velocity for at least up to 90% of the total gap.[3] Propagation velocities were found to be proportional to the applied voltage and to decrease with increasing gap. The fact that positive streamer velocity depends upon the gap but not on its position in the gap suggests there exists a regulatory mechanism whereby the field at the streamer tip remains constant.

These research results were put into quantitative electrical terms for switches such as those on Casino or Aurora/AMP by positing that the positive tree-streamer behaves capacitively as if the anode were supersonically moving toward the cathode at

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the tree-streamer growth velocity (Figure 3-top). The electrical model which was developed to represent this effect is shown in Figure 3-lower. The model describes an anode-streamer switch which transfers energy from a negatively-charged pulseforming line connected at node A to a transformer or diode connected at node B.

The components R_w and C_w represent the undisturbed water resistance and capacitance of the gap and are coupled by the relationship,

$$R_w C_w = \frac{\varepsilon}{\sigma}$$

where ε and σ are the water permittivity and conductivity respectively. Similarly R_{ws} and C_{ws} represent the undisturbed water resistance and capacitance from the anode tree/streamer tips to the cathode at A. R_s and L_s represent the equivalent bush/streamer resistance and inductance respectively. It is assumed that an onset time exists before which no anode tree structure exists in the gap. At instants of time before onset only components R_w and C_w are connected in the model and R_{ws}, C_{ws}, R_s and L_s are disconnected.

Application to Casino

The switch model was inserted into the Casino lumped parameter generator model which was derived from the existing coaxial line model for the accelerator. Computer predictions of the transient pulseline voltage preclosure "rounding" and postclosure damping effects were then compared with observed voltage waveforms for the water switch (Figure 4) and a gas switch[1] being tested on Casino. Preclosure rounding was well fit by invoking volume-extensive capacitive coupling between the interelectrode anode trees and the opposite switch cathode. This volume-extensive coupling required that the entire active switch volume be eventually filled with conducting branches and pathways (bushes and trees). For the Casino water switch, propagation velocity for anode tree growth was taken to be 5 x 10^5 meters per second based on estimates from Casino water switch closure-time measurements. For the gas switch a propagation velocity of 1 x 10^7 meters per second was necessary to fit the observed preclosure rounding. To obtain agreement in the postclosure waveform region it was necessary for R_s and L_s to take on the time-dependent values shown in Figures 4 and 5. The times t_o, t_c, t_{1p} and t_{2p} are respectively the time of streamer onset, streamer closure, first voltage maximum and second voltage minimum. Peak current passes through the switch between t_c and t_{1p} hence the switch resistance and inductance during that time interval are critical to power output and energy transfer. These values imply the lack of current sharing between streamer paths in late time as a result perhaps of some paths becoming extinguished.

Application to Aurora/AMP

The Aurora/AMP generator differs significantly from Casino in that two switches - one at the input and one at the output of the pulseforming line - are critical. Computer predictions of the pulseline voltage waveforms using a Aurora/AMP lumped-parameter generator model derived from the distributive coaxial line model with a modeled or "real" input switch as described here (Figure 2-lower) and an ideal, lossless, instantaneously-closing output switch are shown in Figure 6. The middle curve is the predicted voltage when a streamer resistance R_s of 2.45 ohms and a propagation velocity of $2x10^6$ meters per second are used in the input switch model. The lowest curve is the predicted voltage when both output and input switches are ideal, lossless, instantaneously-closing switches. The upper curve is the available measured data which did not extend beyond $2.10x10^{-6}$ seconds and was replaced arbitrarily by a zero baseline in this region. This surprisingly good fit to the observed waveform was achieved solely on the basis of assuming an input switch streamer resistance R_s of 2.45 ohms which was scaled from the Casino water switch results. An equally good fit to the observed pulseline voltage can be achieved by using a "real" output switch as described in this paper and positing preclosure volume-extensive capactive coupling to the downstream transformer sections. Consequently the significant reduction (∿20%) in peak pulse line voltage from that of the ideal-input, ideal-output switch prediction, can be explained equally well by two distinct mechanisms: input switch postclosure resistance or output switch preclosure capacitive coupling. When additional streamer propagation information for the switches and postclosure damped-waveform data has been obtained the relative importance of these two mechanisms will undoubtedly be established.

Results

An electrical streamer-switch model has been developed and successfully applied to (1) the Casino high-voltage water switch and (2) a gas switch under test in the same accelerator. Spatially-extensive capacitive coupling of supersonic tree/streamers traveling at 5 x 10^5 meters per second for the water switch and traveling 1 x 10^7 meters per second for the gas switch successfully explain the observed preclosure rounding effects. A time-dependent streamer-arc resistance and inductance was required to predict the observed postclosure pulseline voltage peaks and frequency. The arc resistance of the Casino water switch and of the gas switch was determined by computer sensitivity calculations to be 0.5 $\pm$ 0.1 ohms and 0.3 $\pm$ 0.06 ohms respectively, during the time of peak current in the power pulse. Energy dissipated in these water and gas switches, also during the first pulse, was 19.9 kJ and 12.4 kJ respectively out of 110 kJ stored in the pulseline.

An extension of these results to Aurora/AMP has succeeded in matching the observed waveforms and computer predictions suggest that two streamer-switch mechanisms, arc-streamer resistance in the input switch and spatially-extensive streamer capacitance in the output switch, are playing important roles in the pulsed-power produced by this generator. Accurate description of the Aurora/AMP pulseforming line voltage requires more accurate experimental determination of the streamer propagation velocity in both input and output switches and a determina-

tion of the postclosure damped waveforms for the system.

Conclusions

The role of switch streamers in accounting for the power output and energy balance in pulse power accelerators has been more clearly established by the introduction of an electrical streamer-switch model which describes the electrical effects taking place in large-area, high-voltage water switches. The streamer switch model reflects the importance of arc-streamer mechanisms in the breakdown of the water insulant. Streamer effects are of obvious importance in elucidating the mechanisms of electrical breakdown and, as illustrated by this work, are also important in establishing the electrical effects of those breakdown mechanisms in large machines where propagation velocity is a controlling factor. It is hoped that switch models as herein proposed, will become useful tools in the improvement and future design of pulsed-power accelerators.

Future effort with this model is being focused (1) on its application to Aurora/AMP and other machines, (2) its application to the development of high-power gas switches, and (3) on the development of current-dependent components that are consistent with streamer channel formation energies and hydrodynamic shock effects in water.

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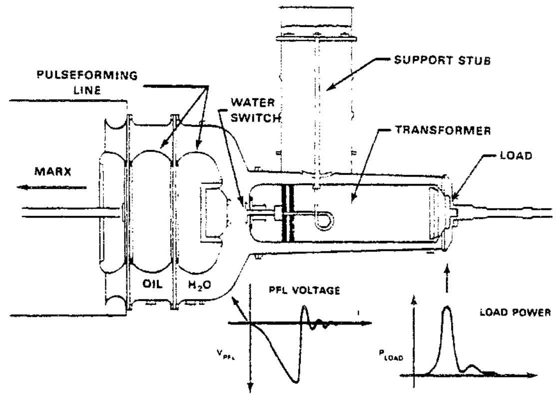


Fig. 1. Section view of the Casino generator.

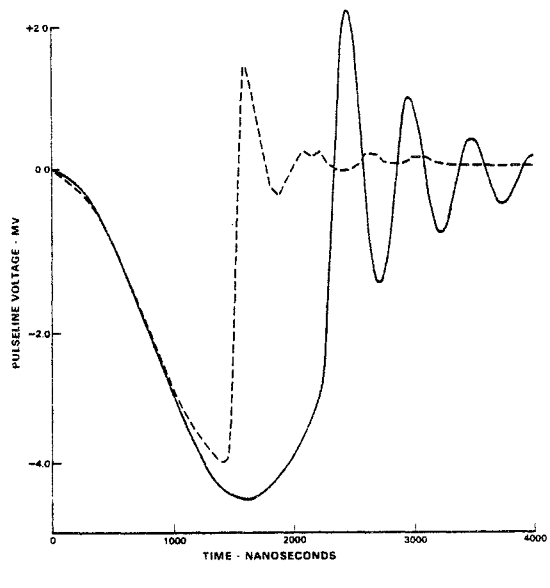
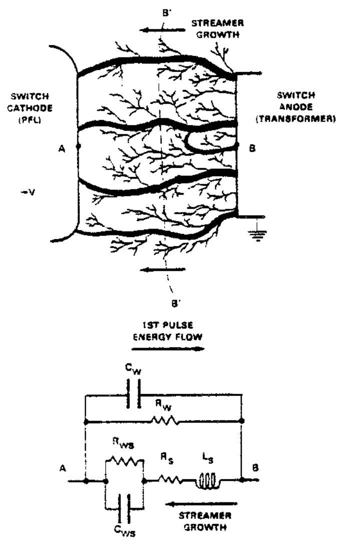


Fig. 2. Comparison of Casino pulseforming line (pfl) voltage rounding due to switch streamers (dashed) and due to resonance charging peak when switch is not closed Same Marx charge is used in both shots.



ig. 3. Positive tree growth showing heavy streamer channels that eventually form (top) and the electrical switch model of the process (bottom).

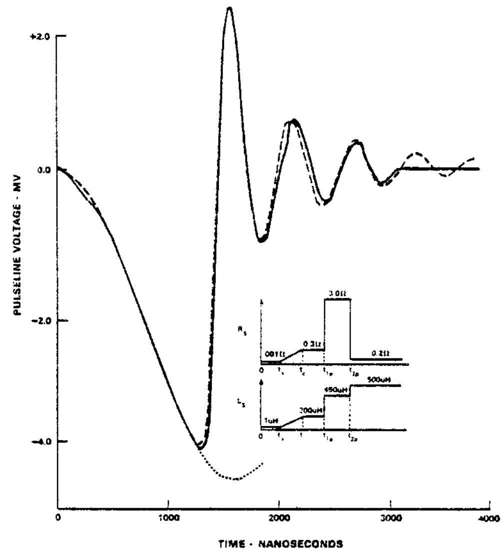
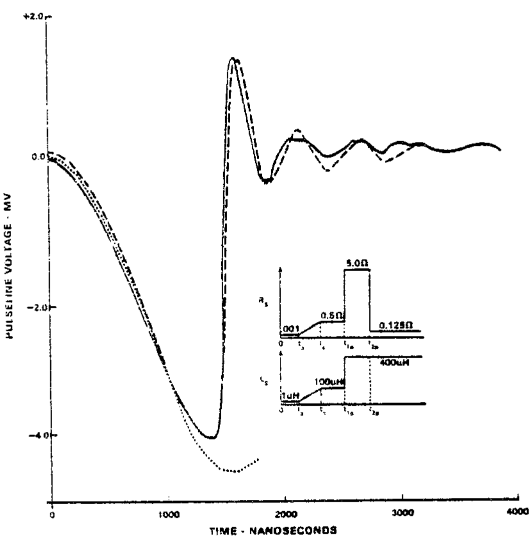


Fig. 5. Pfl voltage for a gas switch under test on Casino comparing measured (—) and model (- -) with $1x10^7$ meters per second streamer propagation velocity and a switch gap = 0.529 meters.



ig. 4. Pfl voltage for the Casino water switch comparing measured (—) and model (- -) with $5x10^5$ meters per second streamer propagation velocity and a switch gap = 0.219 meters.

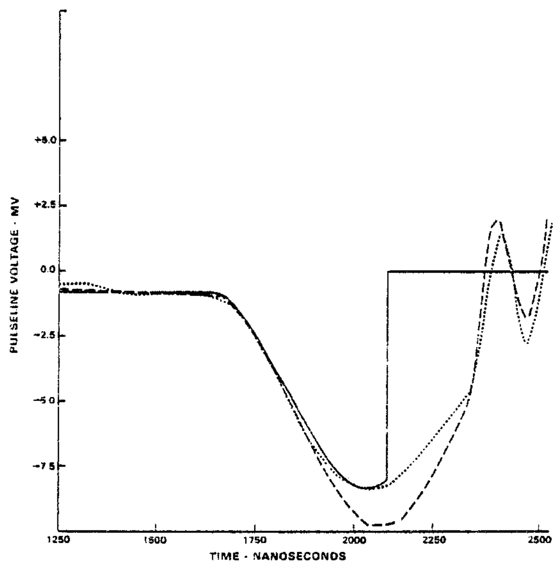


Fig. 6. Pfl voltage for Aurora/AMP water switches comparing (—) and model (···). The input switch streamer resistance, R_S was taken to be 2.45 ohms while the output switch was ideal. Dashed curve is pfl voltage if both input and output switches are ideal.